Inclusive Search for a Highly Boosted Higgs Boson Decaying to a Bottom Quark-Antiquark Pair

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An inclusive search for the standard model Higgs boson (H) produced with large transverse momentum (p_T) and decaying to a bottom quark-antiquark pair ($b\bar{b}$) is performed using a data set of pp collisions at $\sqrt{s} = 13$ TeV collected with the CMS experiment at the LHC. The data sample corresponds to an integrated luminosity of 35.9 fb^{-1}. A highly Lorentz-boosted Higgs boson decaying to $b\bar{b}$ is reconstructed as a single, large radius jet, and it is identified using jet substructure and dedicated b tagging techniques. The method is validated with $Z \to b\bar{b}$ decays. The $Z \to b\bar{b}$ process is observed for the first time in the single-jet topology with a local significance of 5.1 standard deviations (5.8 expected). For a Higgs boson mass of 125 GeV, an excess of events above the expected background is observed (expected) with a local significance of 1.5 (0.7) standard deviations. The measured cross section times branching fraction for production via gluon fusion of $H \to b\bar{b}$ with reconstructed $p_T > 450$ GeV and in the pseudorapidity range $-2.5 < \eta < 2.5$ is $74 \pm 48(\mathrm{stat})^{+17}_{-10}(\mathrm{syst})$ fb, which is consistent within uncertainties with the standard model prediction.

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In the standard model (SM) [1–3], the Brout-Englert-Higgs mechanism [4–8] is responsible for electroweak symmetry breaking and the mass of elementary particles. Although a Higgs boson (H) was discovered [9–11], the LHC data sets of pp collisions at $\sqrt{s} = 7$ and 8 TeV were not sufficient to establish the coupling to bottom quarks [12], despite the 58.1% expected branching fraction of the Higgs boson to bottom quark-antiquark ($b\bar{b}$) pairs [13]. The most sensitive method to search for $H \to b\bar{b}$ decays at a hadron collider is to use events in which the Higgs boson is produced in association with a W or Z boson (VH) decaying to leptons, and recoiling with a large transverse momentum (p_T) [14], in order to suppress the overwhelming irreducible background from quantum chromodynamics (QCD) multijet production of b quarks. Because of this background, an observation of $H(b\bar{b})$ decays in the gluon fusion production mode (GGF) as considered impossible. This Letter presents the first inclusive search for $H \to b\bar{b}$, where the Higgs boson is produced with high-p_T. Measurements of high-p_T $H(b\bar{b})$ decays may resolve the loop induced and tree-level contributions to the GGF process [15] and provide an alternative approach to study the top quark Yukawa coupling in addition to the $t\bar{t}H$ process.

The results reported in this Letter are based on a data set of pp collisions at $\sqrt{s} = 13$ TeV, collected with the CMS detector at the LHC in 2016, and corresponding to an integrated luminosity of 35.9 fb^{-1}. The main experimental difficulties for this search originate from the large cross section for background multijet events at low jet mass and the restrictive trigger requirements needed to reduce the data recording rate. Therefore, we require events to have a high-p_T Higgs boson candidate and define six p_T categories from 450 GeV to 1 TeV with variable width from 50 to 200 GeV. Combinatorial backgrounds are reduced by requiring the Higgs boson's decay products to be clustered in a single jet [14]. The jet is required to have a two-prong substructure and b tagging properties consistent with the $H(b\bar{b})$ signal. The nontrivial jet mass shape is difficult to model parametrically. For this reason, the dominant background from SM QCD multijet production is estimated in data by inverting the b tagging requirement, which is, by design, decorrelated from jet mass and p_T. A simultaneous fit to the distributions of the jet mass in all categories is performed in the range 40 to 201 GeV to extract the inclusive $H(b\bar{b})$ and $Z(b\bar{b})$ production cross sections and to determine the normalizations and shapes of the jet mass distributions for the backgrounds.

A detailed description of the CMS detector, together with a definition of the coordinate system and the relevant kinematic variables, can be found in Ref. [16]. The central feature of the CMS apparatus is a superconducting solenoid

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of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two end cap sections, reside within the solenoid. Forward calorimeters extend the pseudorapidity (η) [16] coverage provided by the barrel and end cap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

Simulated samples of signal and background events are produced using various Monte Carlo (MC) event generators, with the CMS detector response modeled using the GEANT4 [17] program. The MADGRAPH5_aMC@NLO 2.3.3 [18] generator is used for the diboson, $W+\text{jets}$, $Z+\text{jets}$, QCD multijet samples at leading order (LO) accuracy, with matching [19] between jets from the matrix element calculation and the parton shower description, while POWHEG 2.0 [20–22] at next-to-leading order (NLO) precision is used to model the $t\bar{t}$ and single-top processes. For parton showering and hadronization, the POWHEG and MADGRAPH5_aMC@NLO samples are interfaced with PYTHIA 8.212 [23]. The PYTHIA parameters for the underlying event description are set to the CUETP8M1 tune [24]. The production cross sections for the diboson samples are calculated to next-to-next-to-leading-order (NNLO) accuracy with the MCFM 7.0 program [25]. The cross section for top quark pair production is computed with TOP++ 2.0 [26] at NNLO. The cross sections for $W+\text{jets}$ and $Z+\text{jets}$ samples include higher-order QCD and electroweak (EW) corrections and improve modeling of high-p_T W and Z bosons events [27–30]. The parton distribution function (PDF) set NNPDF3.0 [31] is used to produce all simulated samples, with the accuracy (LO or NLO) corresponding to that of the generator used. The Higgs boson signal samples are produced using the POWHEG event generator with $m_H = 125$ GeV. For the GGF production mode, the POWHEG generated sample with up to one extra jet in matrix element calculations is normalized to the inclusive cross section at next-to-next-to-next-to-leading order ($\mathrm{N^3LO}$) accuracy [32–35]. The resulting Higgs boson p_T spectrum neglects the effects of the finite top quark mass [36] and associated higher-order QCD corrections [37–40], which are expected to be large for p_T greater than approximately twice the mass of the top quark [36]. A p_T-dependent correction has been derived to account for both of these effects. The POWHEG GGF p_T spectrum is reweighted to the 0–2 jet CKKW-L [26,41,42] merged LO GGF process incorporating the finite top quark mass (m_t) [13,43–45]. This spectrum is then corrected by the approximate NLO to LO ratio, obtained by expanding in powers of $1/m_t^2$ up to $1/m_t^4$, and the effective NNLO to NLO ratio [46,47] in the infinite top quark mass approximation. The overall p_T-dependent correction to the initial $\mathrm{N^3LO}$ POWHEG GGF spectrum is found to be 1.27 ± 0.38, resulting in a GGF cross section times $H(b\bar{b})$ branching fraction of 31.7 ± 9.5 fb for reconstructed Higgs boson $p_T > 450$ GeV and $|\eta| < 2.5$. An uncertainty of 30% to the overall correction is estimated from the comparison of different predictions obtained by using (i) a merging scale of 100 instead of 20 GeV, (ii) the inclusive two-jet GGF process generation, and (iii) the MADGRAPH5_aMC@NLO effective field theory approximation [13,46] normalized to the inclusive $\mathrm{N^3LO}$ cross section. The p_T spectrum of the Higgs boson for the vector boson fusion (VBF) production mode is reweighted to account for $\mathrm{N^3LO}$ corrections to the cross section. These corrections [48,49] have a negligible effect on the yield for this process for events with Higgs boson $p_T > 450$ GeV.

The particle-flow event algorithm [50] is employed to reconstruct and identify each individual particle with an optimized combination of information from the various elements of the CMS detector. The algorithm identifies each reconstructed particle as an electron, a muon, a photon, or a charged or a neutral hadron. The missing transverse momentum vector is defined as the negative vectorial sum of the transverse momenta of all the particles identified in the event, and its magnitude is referred to as p_T^{miss}.

The particles are clustered into jets using the anti-k_T algorithm [51] with a distance parameter of 0.8 (AK8 jets). To mitigate the effect of pileup, the pileup per particle identification (PUPPI) algorithm [52] assigns a weight to each particle prior to jet clustering based on the likelihood of the particle originating from the hard scattering vertex. Further corrections are applied to the jet energy as a function of jet η and p_T to account for detector response nonlinearities.

To isolate the Higgs boson signal, a high-p_T signal jet is required. Combinations of several online selections are used, all requiring the total hadronic transverse energy in the event (H_T) or jet p_T to be above a given threshold. In addition, a minimum threshold on the jet mass is imposed after removing remnants of soft radiation with the jet trimming technique [53] to reduce the H_T or p_T thresholds and improve the signal acceptance. The online selection is fully efficient at selecting events offline with at least one AK8 jet with $p_T > 450$ GeV and $|\eta| < 2.5$. Events containing identified and isolated electrons, muons, or τ leptons with $p_T > 10$, 10, or 18 GeV and $|\eta| < 2.5$, 2.4, or 2.3, respectively, are vetoed to reduce backgrounds from SM EW processes. Since no genuine p_T^{miss} is expected for signal processes, events with $p_T^{\text{miss}} > 140$ GeV are removed in order to further reduce the top quark background contamination. The leading (in p_T) jet in the event is assumed to be the Higgs boson candidate, the H jet. The soft-drop algorithm [54,55] is used to remove soft and wide-angle radiation with a soft radiation fraction z less than 0.1. The parameter β is set to zero, which corresponds to the case in which approximately the same fraction of energy is groomed away, regardless of the initial jet energy.

The use of soft-drop grooming reduces the jet mass (m_{SD}) for background QCD events when large jet masses arise from soft gluon radiation. For signal events, the jet mass is primarily determined by the $H(b\bar{b})$ decay kinematics and its distribution peaks at the mass of the Higgs boson. Dedicated m_{SD} corrections [56] are derived from simulation and data in a region enriched with merged $W(q\bar{q})$ decays from $t\bar{t}$ events. They remove a residual dependence on the jet p_T and match the jet mass scale and resolution to those observed in data.

The dimensionless mass scale variable for QCD jets, $\rho = \log(m_{\mathrm{SD}}{}^2/p_T{}^2)$ [54,57], whose distribution is roughly invariant in different ranges of jet p_T, is used to characterize the correlation between the jet b tagging discriminator, jet mass, and jet p_T. Only events in the range $-6.0 < \rho < -2.1$ are considered, to avoid instabilities at the edges of the distribution due to finite cone limitations from the AK8 jet clustering ($\rho \gtrsim -2.1$) and to avoid the nonperturbative regime of the soft-drop mass calculation ($\rho \lesssim -6.0$). This requirement is fully efficient for the Higgs boson signal.

The N_2^1 variable [58], which is based on a ratio of 2-point and 3-point generalized energy correlation functions (ECFs) [59], is exploited to determine how consistent a jet is with having a two-prong substructure. The calculation of N_2^1 is based on the jet constituents after application of the soft-drop grooming algorithm to the jet. It provides excellent discrimination between two-prong signal jets and QCD background jets [58]. However, any selection on N_2^1 or other similar variables [60] shapes the jet mass distributions differently depending on the p_T of the jet. Therefore a transformation of N_2^1 to $N_2^{1,\mathrm{DDT}}$ is applied, where DDT stands for designed decorrelated tagger [57], to reduce its correlation with ρ and p_T in multijet events. We define $N_2^{1,\mathrm{DDT}} = N_2^1 - N_{2(26\%)}^1$, where $N_{2(26\%)}^1$ is the 26th percentile of the N_2^1 distribution in simulated QCD events as a function of ρ and p_T. This ensures that the selection $N_2^{1,\mathrm{DDT}} < 0$ yields a constant QCD background efficiency of 26% across the entire ρ and p_T range considered in this search. The chosen percentile maximizes the sensitivity to the Higgs boson signal. In order to select events in which the H jet is most likely to contain two b quarks, we use the double-b tagger algorithm [61]. Several observables that characterize the distinct properties of b hadrons and their flight directions in relation to the jet substructure are used as input variables to this multivariate algorithm in order to distinguish between H jets and QCD jets. An H jet is considered double-b tagged if its double-b tag discriminator value is above a threshold corresponding to a 1% misidentification rate for QCD jets and a 33% efficiency for $H(b\bar{b})$ jets.

Events with (without) a double-b tagged H jet define the passing (failing) region. In the passing region, the gluon fusion process dominates, although other Higgs boson production mechanisms contribute: VBF (12%), VH (8%), and $t\bar{t}H$ (5%). They are all taken into account when extracting the Higgs boson yield.

The contribution of $t\bar{t}$ production to the total SM background is estimated to be less than 3%. It is obtained from simulation corrected with scale factors derived from a $t\bar{t}$-enriched control sample in which an isolated muon is required. This sample is included in a global fit used to extract the signal and the scale factors are treated as unconstrained parameters. They multiply the $t\bar{t}$ contribution, correcting its overall normalization and the double-b mistag efficiency for jets originating from top quark decays.

The main background in the passing region, QCD multijet production, has a nontrivial jet mass shape that is difficult to model parametrically and dependent on jet p_T, so we constrain it using the signal-depleted failing region. Since the double-b tagger discriminator and the jet mass are largely uncorrelated, the passing and failing regions have similar QCD jet mass distributions, and their ratio, the "pass-fail ratio" $R_{p/f}$, is expected to be nearly constant as a function of jet mass and p_T. To account for the residual difference between the shapes of passing and failing events, $R_{p/f}$ is parametrized as a polynomial in ρ and p_T, $R_{p/f}(\rho, p_T) = \sum_{k,\ell} a_{k\ell}\rho^k p_T^\ell$. The coefficients $a_{k,\ell}$ have no external constraints but are determined from a simultaneous fit to the data in passing and failing regions across the whole jet mass range. To determine the order of the polynomial necessary to fit the data, a Fisher F-test [62] is performed. Based on its results, a polynomial of second order in ρ and first order in p_T is selected.

The systematic uncertainties associated with the jet mass scale, the jet mass resolution, and the $N_2^{1,\mathrm{DDT}}$ selection efficiency are correlated among the W, Z, and $H(b\bar{b})$ processes. These uncertainties are estimated using an independent sample of merged W jets. Additional details are available in the Supplemental Material [63], which includes Ref. [64]. The efficiency of the double-b tagger is measured in data and simulation in a sample enriched in $b\bar{b}$ from gluon splitting [61]. Scale factors relating data and simulation are then computed and applied to the simulation. These scale factors determine the initial distributions of the jet mass for the $W(q\bar{q})$, $z(q\bar{q})$, and $H(b\bar{b})$ processes, and they are further constrained in the fit to data due to the presence of the W and Z resonances in the jet mass distribution. The uncertainty associated with the modeling of the GGF Higgs p_T spectrum is propagated to the overall normalization of the GGF Higgs signal. In addition, the shape of the GGF Higgs p_T distribution is allowed to vary depending on the Higgs boson p_T by up to 30% at 1000 GeV, without changing the overall normalization. To account for some potentially p_T-dependent deviations due to missing higher-order corrections, uncertainties are applied to the $W(q\bar{q})$ and $Z(q\bar{q})$ yields that are p_T-dependent and correlated per p_T bin. An additional

TABLE I. Summary of the systematic uncertainties affecting the signal, W and $Z+$jets processes. Instances where the uncertainty does not apply are indicated by "…".

Systematic source	W/Z	H
Integrated luminosity	2.5%	2.5%
Trigger efficiency	4%	4%
Pileup	$<1\%$	$<1\%$
$N_2^{1,\mathrm{DDT}}$ selection efficiency	4.3%	4.3%
Double-b tag	4% (Z)	4%
Jet energy scale/resolution	10/15%	10/15%
Jet mass scale (p_T)	0.4%/100 GeV (p_T)	0.4%/100 GeV (p_T)
Simulation sample size	2–25%	4–20% (GGF)
H p_T correction	…	30% (GGF)
NLO QCD corrections	10%	…
NLO EW corrections	15–35%	…
NLO EW W/Z decorrelation	5–15%	…

systematic uncertainty is included to account for potential differences between the W and Z higher-order corrections (EW W/Z decorrelation). Finally, additional systematic uncertainties are applied to the $W(q\bar{q})$, $Z(q\bar{q})$, and $H(b\bar{b})$ yields to account for the uncertainties due to the jet energy scale and resolution [65], variations in the amount of pileup, and the integrated luminosity determination [66]. A quantitative summary of the systematic effects considered is shown in Table I.

In order to validate the background estimation method and associated systematic uncertainties, studies are performed on simulated samples injecting signal events and determining the bias on the measured signal cross section. No significant bias is observed in these studies.

A binned maximum likelihood fit to the observed m_{SD} distributions in the range 40 to 201 GeV with 7 GeV bin width is performed using the sum of the $H(b\bar{b})$, W, Z, $t\bar{t}$, and QCD multijet contributions. The fit is done simultaneously in the passing and failing regions of the six p_T categories within $450 < p_T < 1000$ GeV, and in the $t\bar{t}$-enriched control region. The production cross sections relative to the SM cross sections (signal strengths) for the Higgs and the Z bosons, μ_H and μ_Z, respectively, are extracted from the fit. Figure 1 shows the m_{SD} distributions in data for the passing and failing regions with measured SM background and $H(b\bar{b})$ contributions. Contributions from W and Z boson production are clearly visible in the data.

The measured Z boson signal strength is $\mu_Z = 0.78 \pm 0.14(\mathrm{stat})^{+0.19}_{-0.13}(\mathrm{syst})$, which corresponds to an observed significance of 5.1 standard deviations (σ) with 5.8σ expected. This constitutes the first observation of the Z boson signal in the single-jet topology [67] and validates the substructure and b tagging techniques for the Higgs boson search in the same topology. The measured cross section for the $Z+$jets process for jet $p_T > 450$ GeV and $|\eta| < 2.5$ is $0.85 \pm 0.16(\mathrm{stat})^{+0.20}_{-0.14}(\mathrm{syst})$ pb, which is

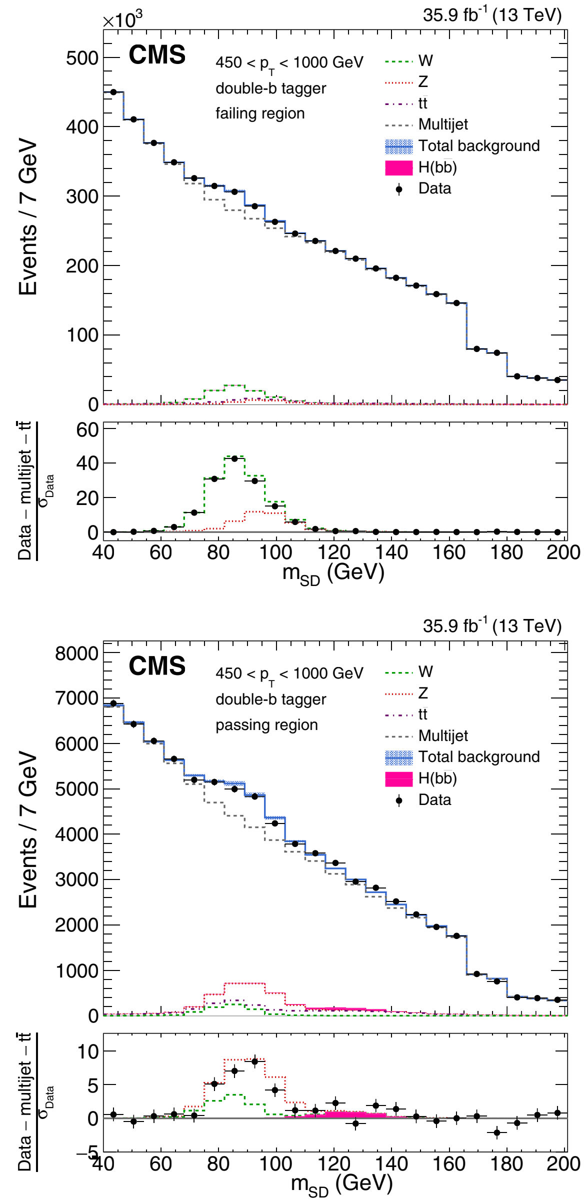

FIG. 1. The m_{SD} distributions in data for the failing (left) and passing (right) regions and combined p_T categories. The QCD multijet background in the passing region is predicted using the failing region and the pass-fail ratio $R_{\mathrm{p/f}}$. The features at 166 and 180 GeV in the m_{SD} distribution are due to the kinematic selection on ρ, which affects each p_T category differently. In the bottom panel, the ratio of the data to its statistical uncertainty, after subtracting the nonresonant backgrounds, is shown.

TABLE II. Fitted signal strength, expected and observed significance of the Higgs and Z boson signal. The 95% confidence level upper limit (UL) on the Higgs boson signal strength is also listed.

	H	H no p_T corrections	Z
Observed signal strength	$2.3^{+1.8}_{-1.6}$	$3.2^{+2.2}_{-2.0}$	$0.78^{+0.23}_{-0.19}$
Expected UL signal strength	<3.3	<4.1	...
Observed UL signal strength	<5.8	<7.2	...
Expected significance	0.7σ	0.5σ	5.8σ
Observed significance	1.5σ	1.6σ	5.1σ

consistent within uncertainties with the SM production cross section of 1.09 ± 0.11 pb [30]. Likewise, the measured Higgs boson signal strength is $\mu_H = 2.3 \pm 1.5(\mathrm{stat})^{+1.0}_{-0.4}(\mathrm{syst})$ and includes the corrections to the Higgs boson p_T spectrum described earlier. The corresponding observed (expected) upper limit on the Higgs boson signal strength at a 95% confidence level is 5.8 (3.3), while the observed (expected) significance is 1.5σ (0.7σ). The observed μ_H implies a measured GGF cross section times $H(b\bar{b})$ branching fraction for jet $p_T > 450$ GeV and $|\eta| < 2.5$ of $74 \pm 48(\mathrm{stat})^{+17}_{-10}(\mathrm{syst})$ fb, assuming the SM values for the ratios of the different $H(b\bar{b})$ production modes. This measurement is consistent within uncertainties with the SM GGF cross section times $H(b\bar{b})$ branching fraction of 31.7 ± 9.5 fb.

Table II summarizes the measured signal strengths and significances for the Higgs and Z boson processes. In particular, they are also reported for the case in which no corrections to the Higgs boson p_T spectrum are applied. Figure 2 shows the profile likelihood test statistic scan in data as function of the Higgs and Z boson signal strengths (μ_H, μ_Z).

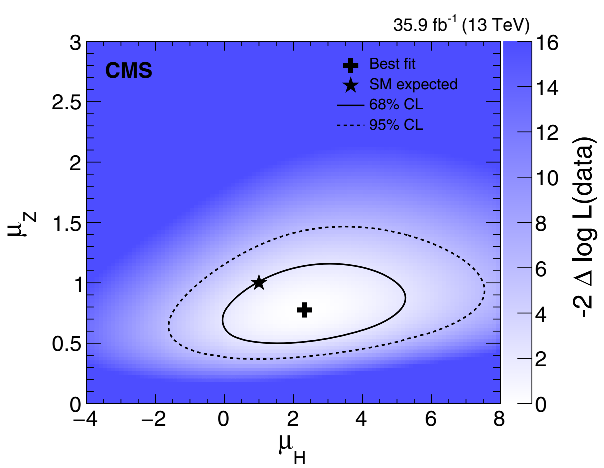

FIG. 2. Profile likelihood test statistic $-2\Delta \log \mathcal{L}$ scan in data as a function of the Higgs and Z bosons signal strengths (μ_H, μ_Z).

In summary, an inclusive search for the standard model Higgs boson with $p_T > 450$ GeV decaying to bottom quark-antiquark pairs and reconstructed as a single, large-radius jet is presented. The Z + jets process is observed for the first time in the single-jet topology with a significance of 5.1σ. The Higgs production is measured with an observed (expected) significance of 1.5σ (0.7σ) when including Higgs boson p_T spectrum corrections accounting for higher-order and finite top quark mass effects. The measured cross section times branching fraction for the gluon fusion $H(b\bar{b})$ production for reconstructed p_T and $|\eta| < 2.5$ is $74 \pm 48(\mathrm{stat})^{+17}_{-10}(\mathrm{syst})$ fb, which is consistent with the SM prediction within uncertainties.

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